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Wind Turbines on Ships

Development and Demonstration of

New Technology for the use of

Wind Turbines on Ships - Phase 2

A research project with support from

The Swedish Energy Agency

Region Västra Götaland

Lloyd's Register AB

Stena Rederi AB

PROPit AB

Gothenburg
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The insightful results from the project could be produced only thanks to the dedicated efforts from the team of more than fifteen researchers and technical consultants, who are listed as authors under the section "References" at the end of this summarizing report. In addition, much work in outdoor winter conditions was done by Magnus Ellse'n, Chalmers, Eric Norelius, PROPit, Lars Björkström, Svensk Klimatelektronik and Ulf Möller. Ö-Varvet at Öckerö, with Jonas Backman and Bo Bengtsson were instrumental in designing and preparing the model tanker, Airmax and Andreas Långström, SSPA supported with his competence and experience from making sea trials with Airmax.

The project was coordinated through a Steering Group, with
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Valuable input and advice to the editing of this summarizing report were received from the Steering Group and from Anders Wickström, Scandinavian Wind AB.

Executive Summary

The start-up company PROPit AB has developed a concept for harnessing sea winds for simultaneous electricity generation and thrust, by using conventional, but modified wind turbines onboard merchant vessels. The primary market should be tankers and bulk ships with large and open deck space, operating on routes and in areas with favourable wind conditions. The business idea is to create substantial fuel savings while simultaneously reducing harmful greenhouse gas emissions.

This is the third consecutive research project which has been completed since 2011 under the management of Chalmers University of Technology, with the objective of establishing sufficient evidence of the feasibility and performance of the technology. This current project has been enabled by the funding of the Swedish Energy Agency and the Region Västra Götaland and with the industrial support from Stena Rederi AB, Lloyd's Register and PROPit AB.

The project's objectives were to enhance knowledge within three domains

- the design of an optimal wind turbine including a dynamic control system
- important stakeholder opinions about the introduction of such a novel technology
- evaluation of conditions and preliminary planning for a demonstration project

Through extensive measurement campaigns at sea with a prototype wind turbine mounted on a model oil tanker in the scale of 1:12, significant amounts of data were recorded and analysed. This was used to validate a developed performance simulation tool which could be applied to various routes and weather conditions, to calculate accumulated yield for a given set of operating variables. An early conclusion in the project was the fact that an active and dynamic control system in itself could enhance the wind turbine's performance with up to thirty percent in comparison with using no control system.

Fuel savings, essentially in conformance with earlier reports, could be estimated but now with higher accuracy. For a Panamax tanker in the North Atlantic, equipped with two one megawatt wind turbines and under a set of given conditions, annual fuel savings around 16 percent have been estimated. Given an HFO price of 354 USD/mt this means that the savings potential could be up to USD 590 000 per year. Certainly, there are high variations for seasons and routes and the research also points to opportunities for technology optimization, before going into commercialization.

In general, attitudes and opinions about the proposed innovation are positive, but to be proven successful, the technology must be adopted by the crew and other stakeholders. The probability of gaining positive green goodwill was suggested in some stakeholder interviews, while all expressed the need to be convinced about the financial benefits.

A demonstration project was designed to last for 16-18 months with a budget around 8-14 mSEK, depending largely on the choice of either a new-designed and -built turbine or a used and modified one. A partial risk assessment indicated no show stoppers but underlined the need for extensive crew training. A demonstration project should be run in three phases, design/construction, onshore operation and verification and sea operation on a merchant ship.

The project's key recommendation is to carry out a large scale demonstration project as a next step towards commercialization. This would include the remaining technical analysis identified in the pre-study, the completion of the risk assessment and technology verification.

Svensk Sammanfattning

Det entreprenörsdrivna företaget PROPit AB har utvecklat ett koncept för att utnyttja vindarna till havs för att kraftigt minska bränsleförbrukningen på stora handelsfartyg. Genom att installera konventionella, men modifierade vindkraftverk kan man både generera elektricitet för användning på fartyget och samtidigt en framåtriktad kraft för att bistå i fartygets framdrivning. Den primära målgruppen är olje- och gastankers samt bulkfartyg med stor, öppen däcksyta, vilka främst opererar i områden med fördelaktiga vindförhållanden. Affärsidén är att samtidigt reducera bränslenotan och minska utsläppen av växthusgaser.

Detta är det tredje forskningsprojektet sedan 2011 under ledning av Chalmers Tekniska Högskola. Syftet har varit att etablera ett tillräckligt kunskapsunderlag kring teknologins produktivitet för att den ska kunna tas till nästa steg mot kommersialisering. Det här projektet har möjliggjorts av finansiering från Statens Energimyndighet och Västra Götalandsregionen samt av industriellt stöd från Stena Rederi AB, Lloyd’s Register och PROPit AB.

Projektets tre mål var att höja kunskapsnivån inom tre områden

- optimal utformning av en vindturbin för dessa driftsförhållanden, inklusive ett dynamiskt styrsystem
- uppfattningen hos viktiga intressentgrupper om hur en sådan ny teknologi kan introduceras i den marina sektorn
- utvärdering av förutsättningarna för och preliminär planering av ett demonstrationsprojekt

Genom omfattande mätkampanjer till sjöss med en vindturbinsprototyp monterad på en modell i skala 1:12 av en oljetanker, har en stor mängd data kunnat samlas och analyseras. Denna information har sedan använts för att validera ett nyutvecklat simuleringsverktyg, vilket i sin tur utnyttjats för att beräkna verkningsgrad och uppskattad bränslebesparing för olika rutter och vindförhållanden och ett antal andra, dokumenterade antaganden. Tidigt i projektet konstaterades att ett aktivt, dynamiskt styrsystem för turbinen i sig själv kunde bidra till att öka dess effekt med upp till trettio procent i jämförelse med att operera den utan ett sådant styrsystem.

Bränslebesparingar i paritet med vad, som visats i tidigare rapporter, har nu kunnat beräknas, men med väsentligt högre säkerhet i kalkylerna. För en Panamax-tanker i Nordatlanten, utrustad med två vindturbiner med vardera märkeffekten en megawatt och under en uppsättning givna variabler, har den årliga besparingen beräknats till sexton procent. Givet ett pris för bunkeroljan på 354 USD/mt, motsvarar det på årlig basis USD 590 000. Det ska tilläggas att det är stora variationer för säsonger och rutter och forskningen pekar samtidigt på ytterligare potential i optimering av teknologin innan konceptet kommersialiseras.

Generellt konstateras att attityder och uppfattningar är positiva till den föreslagna teknologin, i ett antal olika intressentgrupper, vilka kunde beröras av dess genomförande i den marina sektorn. Det är dock viktigt att den primärt accepteras av besättning och andra nära intressenter för att kunna bli en kommersiell framgång. Möjligheten att få en positiv, grön goodwill nämndes i flera intervjuer med intressenter, medan samtliga efterfrågade önskade mer övertygande information om konceptets lönsamhet.

Ett demonstrationsprojekt för en period på 16-18 månader har beskrivits och dess budget uppskattats till cirka 8-14 mSEK. Kostnaden blir starkt beroende av om man väljer att köpa och modifiera en befintlig (använd) vindturbin eller att konstruera och bygga en skräddarsydd turbin i ett lågkostnadsland, sannolikt Kina. Ytterligare arbete har gjorts med en riskanalys och det konstateras att det inte finns några avgörande hinder av riskkaraktär. Däremot pekas omfattande utbildning av besättningen ut, som en viktig faktor för både drift, underhåll och säkerhet. Ett demonstrationsprojekt bör bedrivas i tre faser, med design/konstruktion (alternativt modifiering), driftsättning och drift på land samt till slut genomförande av en längre driftperiod till havs på ett större, oceangående fartyg.

Projektet rekommenderar till slut att ett demonstrationsprojekt i större skala genomförs, som nästa och möjligen sista steg innan teknologin kan kommersialiseras. Detta skulle innefatta återstående teknisk analys och optimering, komplett riskanalys, teknologiverifiering, utbildning och uppföljning av hur installationen uppfattas av berörda intressentgrupper.

Content

1 Introduction

The company PROPit has developed a marine application for conventional wind turbines, to harness sea winds for simultaneous generation of electricity and thrust. The target market is predominantly slow steaming merchant ships with an open deck space, like tankers for oil, gas and chemical products. In this research project Chalmers has undertaken to verify results and conclusions from the previous project phases and to advance knowledge in three domains.

One objective for this current project has been to elaborate on prior fuel saving calculations and to verify calculation methods, in order to improve the robustness of the results. Through sea measurement campaigns in a prototype format, measurement data should be used to validate a newly developed performance simulation model.

The project should also make a preliminary pre-feasibility study for the design, construction, manufacturing and execution of a wind turbine pilot project in near commercial scale.

As a third work package, the project should investigate acceptance and attitudes towards this novel technology, in different stakeholder groups and based on the findings, provide a proposal for a communication plan prior to implementation.

The project was funded by the Swedish Energy Agency and co-funded by Region Västra Götaland. Substantial and valuable support was provided by Stena Rederi AB, Lloyd's Register and PROPit AB.

The project scope was organized in three work packages:

1. Research for optimal fuel savings with wind turbine
2. Technology acceptance
3. Prestudy for a demonstration project

For each of these, detailed reports have been elaborated, providing all background, methodology, calculations and results, including illustrations, tables and images. In order to make this material more easily accessible to a wider audience, this summary report has been edited and compiled. All sub-reports have been listed as references here, but for the ease of reading references have not been included in the various sections. It should be noted that the process of condensing information from a large number of detailed report pages, naturally implies the omission of certain data and references.

Chapter Two describes the basis for performance modelling, more insight into optimal rotor blade design and principles for and estimated effects of active and automated turbine control.

Chapter Three explains the method and the results of a survey of attitudes towards the technology with wind turbines on ships among various stakeholder groups and suggests how communication could be planned in conjunction with a larger scale demonstration project.

Chapter Four gives an account of the work done on a preliminary pre-study for a demonstration project, including a brief analysis of the respective pros and cons of two- and three-bladed turbines.

Based on a prior hazard identification process, an assessment of selected risk elements is also reported in this section.

In Chapter Five the elaborate prototype modifications and measurement campaigns at sea are laid out. There is also included the analysis of the live measurement data from the sea campaigns and the consequential validation of the turbine performance model.

The essential calculations of potential fuel savings for specified North Atlantic routes and different weather conditions are described and commented in Chapter Six. Here the level of accuracy has been elevated in comparison with what was achieved in Phase I. The Chapter concludes with a discussion and the report's final conclusions.

Illustrations, tables and references are listed at the end of the report.

We wish readers enjoyable and interesting reading and invite to making contact for any queries, questions, comments or initiatives.

Gothenburg, Sweden

30th April 2015

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2 Acceptance and attitudes towards wind power on ships

2.1 Introduction

Investments in environmental efforts and sustainable technology often require change in behaviour and how work and routines are conducted. New technological solutions often fail due to lack of end user acceptance and key stakeholder groups not taking enough ownership. One reason for this is likely that initiatives originate from political decisions and/or company policies and not from those who, in the end, will be affected in practice and daily life.

In shipping, many innovations and trends have resulted in unexpected outcomes, one example of which is the concept of eco-driving. Applied in road traffic, almost everyone knows about eco-driving and it is even taught in driving schools. When the concept was introduced in the shipping domain, it was first a success but after a while crews started to compete and their results were used by the management to chase those who were less successful in lowering their fuel consumption. In the end, it became a problem and a source for work environment- and psychosocial problems. Not seldom new technologies and concepts in the marine environment only succeed if they originate from local experts or very senior deck officers who promote and favour its function. It is considered essential that maritime experience and expertise is governing the implementation of any innovation. This should not always be considered a problem but it also aligns well with existing theory on opinions and attitudes. Introducing new technologies and innovations regardless of domain will create opinions that are not always based on true facts and knowledge but rather on rumours and disinformation. Therefore it is necessary to identify the stakeholder groups and their respective opinions and also to potentially provide knowledge and facts to reduce the impact of rumours and speculations.

2.2 Objectives and method

The study should investigate the attitudes and opinions of the maritime cluster towards the use of wind turbines on merchant ships. The purpose was to better understand how new technology gains trust and acceptance. Also, based on the findings, the report should suggest an action plan for how wind turbines can be introduced and how less informed attitudes can be replaced by knowledge.

The study was conducted through semi-structured interviews and the participants were selected through ranked selection criteria. The identification of stakeholders was performed by using a broad spectre of the maritime cluster. The interviewees were given a short introduction to the concept and technical solutions. Twelve interviews were conducted, but despite the relatively low number of interviews, the data appears to be consistent even when compared between stakeholders and not only within one domain.

2.3 Results and discussion

The use of wind turbines on commercial ships is a technological innovation, the purpose and functionality of which must be adopted by the crew and other stakeholders to enhance its chances for success. The most important, perceived advantage and benefit with the introduced technology was that it is sustainable and offers both electrical power and forward thrust contribution to the ship. The feature of folding the turbine on deck was seen as essential. The respondents agreed that the technology would be best suited for ocean going vessels that can plan their voyage with respect to weather and thereby optimize their routes. Concerns were raised about the requirement for new skills for operation and maintenance and regarding noise from the turbine and icing of the wings. The cost of maintenance was also pointed out as a factor to consider.

A few specific challenges were raised, like the need for the system to become an integrated part of other onboard systems, like navigation and machinery, to allow for better route planning and to optimize the turbine utilization. Ship owners said they anticipated resistance from oil companies, due to safety concern and potential negative impact on the cargo. However, the interviewed oil company expressed the need for risk assessments and rather emphasized the potential goodwill with displaying their name in innovative and sustainable, technological solutions.

All interviewees discussed fuel savings both in terms of financial benefits and environmental performance. Many shipping companies are involved in initiatives for clean shipping like clean shipping index (CSI) and environmental shipping index (ESI) because it gives them discounts and also competitive advantages when negotiating new contracts. There are also voices even within shipping companies that it all boils down to making profit and that no shipping company is willing to make a "green" investment before anyone else and before they have seen the financial effects. Sweden and northern Europe are considered innovative. Some claim that a technology like this one could only come from Sweden and probably only has a market here. In this context the potential goodwill was highlighted by some of the stakeholders, stating that as the turbines are highly visible, the probability of gaining much positive attention is high, for both the ship owner and the charterer. The notion of "green electricity" was mentioned as the cargo owners take an increasing interest in how port power supply is generated.

A number of key success factors for the technology were identified, like:

- oil price
- public investment incentives
- front runners, demonstrating the benefits
- onboard ambassadors and charterers supporting the innovation
- Nordic market as role model
- Risk analysis for both safety and working environment

Maybe to somebody's surprise, the oil company and one of the shipping companies transporting oil, expressed no safety concerns or thoughts about perceived risks. Instead, this translated into statements about the need for sufficient crew training for operation and maintenance. Port authorities were hesitant about using the turbine in port. One deck officer said that sailing skills should prove useful when optimizing the use of the turbine and in route planning, which highlights the importance of integrating the turbine control system with the navigational, engine and routing systems.

2.4 Recommendations for introduction of the technology

Efforts should be made to reach out to as many stakeholders as possible with the results from the sea trails, in order to generate a general interest. It seems that a majority of stakeholders are positive to the innovation but need to be convinced about its financial effects. The first step should be to tie a shipping company to the project and to offer a full-scale test bed on which the risk and work environment assessment can be performed along with the technical testing. The sea trials from the current project should be used for highlighting the benefits and for reaching out to potential shipping companies. Since sustainable shipping is a hot topic politically, this should also address current rules and regulations in order to attract attention to initiatives like clean shipping index (CSI) and environmental shipping index (ESI). If investments can be supported or partially funded by grants and also offer the shipping company discounts on port fees etc, the willingness to invest will likely increase. To complement any national political efforts, the international maritime organization (IMO) should also be addressed.

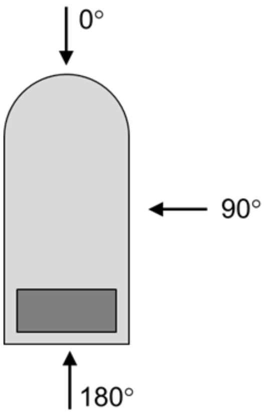
2.5 Conclusions of stakeholder survey

In general, attitudes and opinions about the proposed innovation are positive, from interviewing the identified stakeholders. Efforts should be made to show the result from the sea-based trials with regards to fuel savings and generated power. The next step should include investigating the possibilities of a full-scale trial with active engagement from a shipping company with support from either national, regional or EU funding. Full scale trials should also include efforts to integrate the turbine with systems onboard and be preceded by a comprehensive risk analysis.

3 Wind Turbine Technology for Ship Application

A calculation process and a simulation model to estimate the net yield over a distribution of operating conditions (mainly wind) has been developed. The term "net yield" is used in this report to signify the sum of the contribution from electrical power and thrust.

3.1 Modelling wind turbine performance



The calculation process and tool to integrate the net yield consist of two computations that are performed in series. The first is the calculation of turbine performance, and the second is the integration of net yield for wind conditions on a specific route. The purpose of the turbine performance calculations is to determine the power yield in all operating conditions, relative to the ship. I.e. the yield is calculated for wind speeds from cut-in to cut-out and all inflow directions. It is done by looping over all wind speeds and directions and finding the optimal combination of yaw offset angle, rotor speed and pitch angle.

Figure 1 Definition of wind direction relative to the ship

The second calculation step is to integrate the yield for each external wind condition over the distribution on a representative route taking the speed and heading of the ship into account. It is done by transforming the external global wind conditions to the local moving frame of the ship and calculating the product sum of net yield and wind distribution. The procedure is further described in the flow chart in Figure 2.

The results largely depend on the accuracy in calculations of power and thrust at large yaw offset angles. In order to accurately predict the total yield from the turbine a method that well accounts for power and thrust at high yaw offset angles should be used to compute the turbine performance used as input to the yield accumulation. Such tools are available at Chalmers, either CFD or Vortex methods.

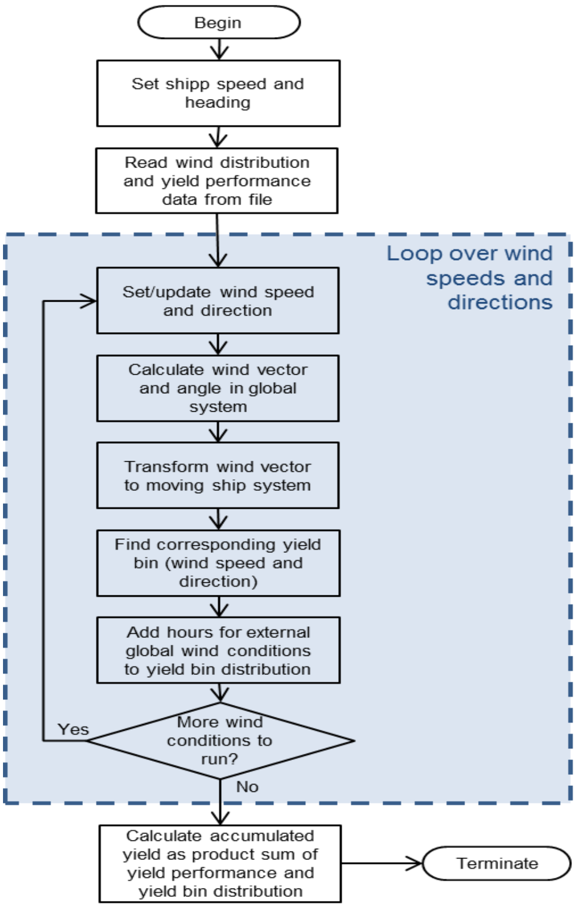


Figure 2 Yield integration flow chart

A comparison shows that when the pitch angle is zero the results, power and thrust, from all calculation methods conform well. The Vortex calculations show a change in pitch sensitivity when the yaw offset increases, applying to both power and thrust. Vidyn results conform well to the Vortex results and do capture the change in pitch sensitivity when yaw offset it changing. Therefore both Vidyn and Vortex calculations can be used to calculate turbine performance for all operating conditions. The results can be used as input to controller set point and accumulated yield calculations. Thereby, the calculations of optimal turbine set points for all wind conditions can be validated and the calculations of accumulated yield from power and thrust combined can be improved. It is recommended that the results are validated by use of such a method.

In a parallel article, a new projection algorithm, that projects the turbine thrust force on the direction of a vessel's heading, is proposed for controlling propulsion. Variations in wind direction and speed are counteracted via turbine yaw offset angle, making the turbine thrust force aligned with the heading of the vessel. A conventional speed controller is modified for varying yaw offset angle and a combined algorithm for simultaneous control of turbine speed and thrust is proposed.

3.2 Turbine and rotor blade design for ship application

Figure 3 is an illustration of the most commonly referred wind turbine components.

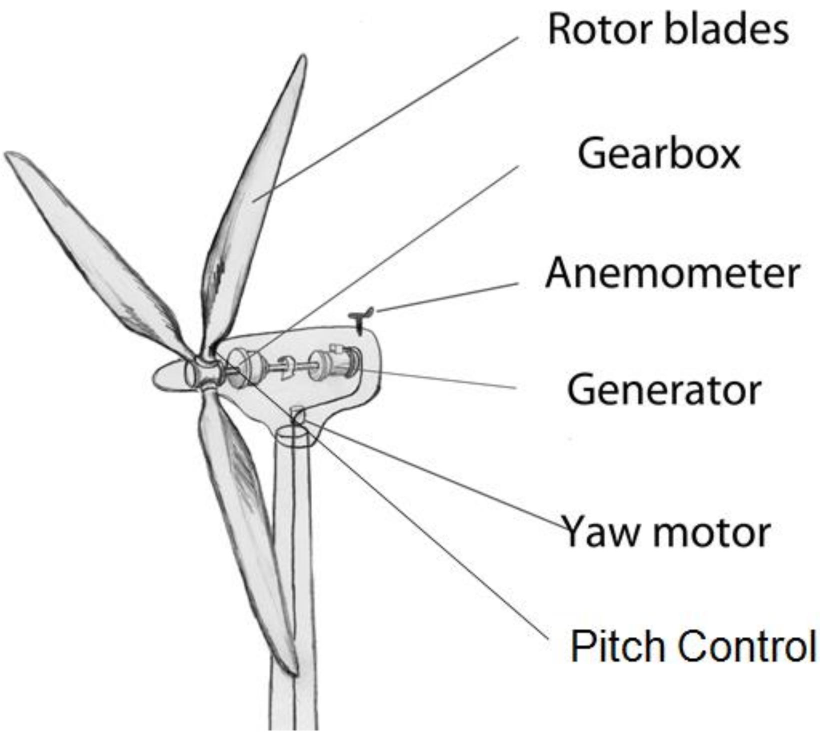


Figure 3 Schematic overview of wind turbine components

The wind turbine market is dominated by three bladed rotors. Two bladed rotors appear less frequently onshore than offshore, due to aspects of access and ease of assembly. Noise, visual appearance and other dynamics (like vibrations) of two bladed rotors have made them less attractive onshore. For installation on ships, the reduced mass and number of components is an advantage of two bladed turbines. The key arguments to select a two bladed turbine would be the possibility to use a larger rotor diameter and the ease of housing the turbine in tilted position.

With the turbine laid down in storm conditions, the blades, regardless of how many, should be horizontal and thus in best possible orientation to minimize the impact of the wind.

The slightly lower efficiency of two bladed turbines will be compensated by the larger diameter, which means the product cost should not heavily depend on the number of blades. While three bladed designs are considered proven technology, there are substantial design challenges in mitigating vibrations when operating at a yaw angle offset, for two bladed turbines. A second concern of two bladed design could be a higher degree of disturbance to the eye of the crew.

A conclusion is that for the early, large(r) scale projects with wind turbines on ships, the safer design is the three bladed rotor. Two bladed rotors add complexity to the already novel design of a mobile turbine installation itself. However, following a reasonable number of successful three bladed turbine installations, a new development step could possibly be to draw on the advantages of two bladed turbines.

A performance analysis aiming to describe design principles for rotor blades for turbines installed on ships was performed with the purpose of exploring the impact of three key blade design parameters:

- chord length
- blade angle
- rotor speed

Performance data were presented for a number of representative operating conditions, to give a hint about how a blade designed for the mobile use on a ship will differ from conventional wind turbine blades. The findings can be used to develop a control strategy in a first step and to arrive at a blade design concept in a second step. The analysis was made for each of the parameters individually, by using the Blade Element Momentum method (BEM). Although BEM does not allow computations for yaw offset, the results could still be validated.

An increase in chord length will increase the generated thrust but not the electrical power. A decrease in chord length will decrease power as well as thrust. Increasing the chord will increase the net yield significantly as long as there is a component of the thrust vector along the ship's heading.

By moderately changing the pitch angle of the blades, the net yield will increase in most operating conditions, depending on wind speed and direction. Net yield can be improved, not only by increasing thrust when the wind is coming from the stern but also by reducing the thrust when the wind is coming from the bow. This is a way of extending the operating range of wind speeds and directions in which the wind turbine will contribute to the ship propulsion and/or electrical power production. Both twist and pitch modification are to be considered in the design of blades and controls for wind turbine application on a ship.

To study the impact of rotor speed, the pitch blade design is adapted (in the model) to produce maximum electrical power at tip speed ratios 6, 7, 8 and 9. The results show that there is an optimum design tip speed ratio between 7 and 8.5 to maximize power and thrust for the pitch blade. In other words, the blade should be designed for a tip speed ratio around 8 and operated at tip speed ratio 9 to maximize yield. Regardless of the design tip speed ratio the rotor speed is a tool to use real-time to trade-off between power and thrust depending on wind speed and direction, to maximize turbine yield.

There is a dilemma, because the thrust has positive value when fully or partly aligned with the ship's heading and it has negative value when fully or partly counter to the ship's heading. Thus, changing the design of the chord, twist distribution or tip speed ratio to increase the thrust will be beneficial in some operating conditions and disadvantageous in others. The question is how big the benefit is when the thrust is aligned with the ship, and how big the drawback is when it is not and how these compare over time. There is a trade-off between maximising the thrust in one case and minimising it in the next. The way to execute the trade-off is to integrate the effects of a design modification over the full range of operating conditions and probability distributions. The applied control strategy will have an impact on the net yield given the wind conditions. Hence it is natural to develop the control strategy first and then to include the resulting effects in the blade design.

3.3 Turbine control strategies

The performance simulation model has been used to quantify the potential for variations of yaw offset, rotor speed and pitch angle and as a result a dynamic turbine control strategy could be presented. It is described as a deviation from conventional, variable speed, pitch control for stationary wind turbines. As a separate assessment, the respective performances of three rotor blade concepts, pitch, stall and symmetric chord were simulated and compared. The average yield in electrical power (kW) was calculated using the annual wind distribution for a specified route. Travel in both directions was considered, assuming constant compass headings and the average of the two was considered representative for the route. Results were presented for ship speeds 7 and 8 m/s, corresponding to 13.6 and 15.6 knots, for calculations with and without the improved controls. In summary, the tailored controls will greatly improve the performance of the turbine. An increase in yield by about 30 % should be expected from optimising yaw offset, rotor speed and pitch angle, which variables have all been optimised simultaneously to obtain the results of this work.

3.4 Results of performance modelling

As stated above, overall turbine performance can be enhanced by up to 30% by adapting an active, dynamic control strategy. The model can also clearly distinguish differing performance between the three rotor blade concepts. A key element when trying to simulate net yield is to understand the impact of true wind on the wind turbine. Figure 4 shows the undisturbed wind distribution on the route from Rotterdam to New York.

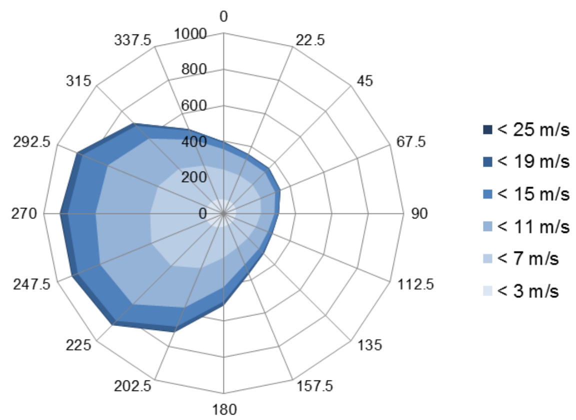


Figure 4 Wind rose for free wind distribution (hours per year) (Rotterdam-New York)

Figure 5 in turn, shows how the wind distribution relative to the turbine is skewed by the ship speed on east and west bound journeys on the route between Rotterdam and New York (Left: west bound journey. Right: east bound journey. 180 deg equals head wind). On the west bound journey there is headwind (180 ±45 degrees) 88 % of the time and on the east bound journey 62 % of the time. Regardless of free wind speed distribution the ships' motion itself will largely influence the wind distribution relative to the wind turbine.

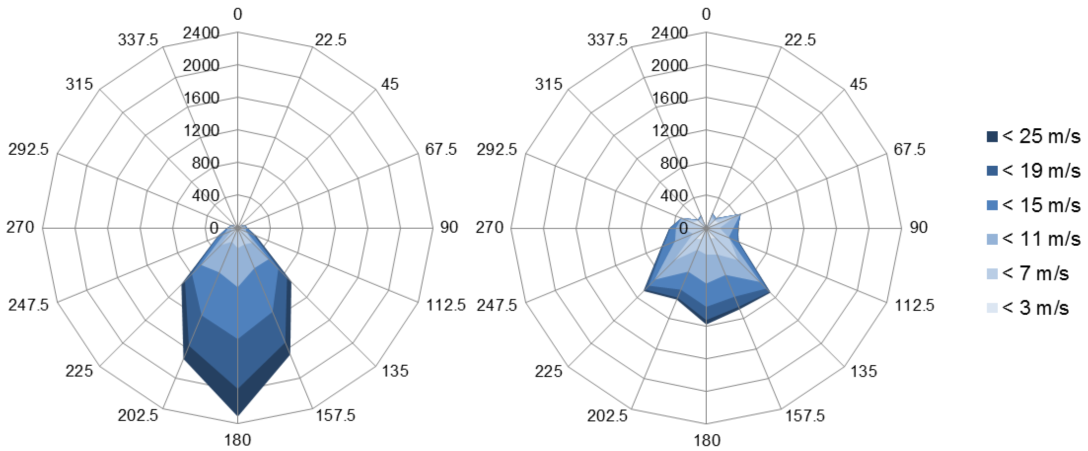


Figure 5 Wind roses for wind distributions (hours per year) relative to ship (Rotterdam–New York)

In Table 1 the effects of power and thrust are compared, where the yield is split into the contribution from those two components. The negative thrust component is a result of the turbine perceiving headwind (relative to the ship) for a large proportion of the time. Depending on the rotor concept, the yield increases 3-7 % when the ship speed is reduced from 8 to 7 m/s.

Table 1 Yield contribution from power and thrust on the Rotterdam–New York route for rotor concepts, all with improved controls

Rotor concept	Ship speed [m/s]	Power yield [kW]			Thrust yield [kW]			Total average yield [kW]
		R-NY	NY-R	Average	R-NY	NY-R	Average	
Pitch	7	560	299	429	-211	-16	-114	316
	8	587	308	447	-247	-35	-141	307
Stall	7	566	308	437	-258	-45	-151	286
	8	578	309	443	-293	-61	-177	266
Symmetric	7	533	278	405	-212	-7	-109	296
	8	550	282	416	-240	-21	-131	285

This study provides useful insight into possible controller strategies and their importance to the performance of a wind turbine on a ship. It is clear that minimising the thrust in situations when it is of no good is at least equally important as maximising it when it helps propel the ship. The results from the performance calculations can be used to define a turbine controller with the objective of maximising yield at any given moment. By adding the value of electrical power to the model all relevant parameters are taken into account. The integration tool can be used to calculate the accumulated average yield on selected routes. It can also be used as a component in a route planning tool. Integrated with a weather forecasting system it enables the dynamic calculation of the most favourable route from a fuel savings perspective.

4 Prototype measurement campaigns and model validation

In the previous research project, completed early 2014, a foldable wind turbine prototype was designed and manufactured. For this current project, Stena Rederi AB allocated their model tanker Airmax for the performance of real sea measurement campaigns. The model ship, in scale 1:12, was modified slightly in order to be able to host the turbine and to provide credible measurement data with regard to positioning, speed and direction.

Additional images and a video from the sea measurement campaigns are available on request to Chalmers.

Figure 6 Airmax during a sea measurement campaign

4.1 Prototype features and modifications

A modification program included equipping the turbine with suitable sensors, developing a robust enough turbine control system and verifying its functionality in a fixed installation at Hönö in the archipelago north-west of Gothenburg. The purpose with this prototype is to measure and verify the interaction between thrust and radial momentum (e g produced electricity) in different wind speeds and different approaching wind angles. The key design features and measurements are reiterated from the phase I project and are listed in Table 2.

Table 2 Prototype features and measurements

Rotor diameter	7 m
Braking load	About 2 500 W
Hub height	6.4 m
Blade configuration	Exchangeable, two and three blades
Alternator voltage	24 V
No of alternators (in series)	3
Adjustable pitch	+/- 3 deg
Weight	750 kg

The design includes a folding mechanism, with a hydraulically operated cylinder. To save weight at the top, the alternators are placed at the bottom and act as counterweights when folding. The rotation movement is transferred to the alternators through a 90 degree angled gear at the top and a steel shaft within the mast.

In the turbine and the ship there are sensors for measuring the important values, such as,

- Wind speed and direction
- Turbine yaw angle
- Turbine rotation speed
- Turbine generator voltage and current.
- Electric power to ships propulsion motors
- Ships propeller shaft speed
- Ships speed, course over ground, compass heading etc. (from a GPS compass)

These variables can be logged in a combined data logger and controller. Necessary software for onshore or offshore operation has been programmed in the controller.

Mechanical modifications: The turbine's structure has been reinforced. The blades have been shortened to a more suitable length. One of the four generators was replaced with a small electric motor, to assist the turbine in starting. The chain drive between the shaft from the turbine and the generators has been reinforced and the gearing has been raised to give a higher generator speed. A new and more robust disc brake has been installed. The function of the blade tip brakes has been adjusted and verified. Initial test runs with two blades and a stiff hub resulted in rather strong tower fluctuations, why a third blade was added, resulting in the fluctuations almost disappearing.

The electrical system: In order to control the turbine speed quickly and accurately enough, a new electrical system was developed and installed. The generators were kept, but connected in series, and the original field control circuits in the generators were removed and replaced with a circuit that can be controlled by the control system. The voltage from the generators is fed into a DC/DC boost converter that in turn on its output is connected to the already installed dump load resistors. The resistors are also connected in series. The DC/DC converter is controlling the generator current, and hence the generator torque. The generator current set point that is fed into the converter comes from the control system.

Measurement sensors: The turbine was equipped with a number of sensors. Most of them are used and are connected to the control system. The turbine speed sensor has been changed to achieve much better resolution and shorter response.

Combined control and measurement system: A controller/measurement system, more suitable to the installed sensors, a CompactRIO platform from National Instruments was programmed in the graphical environment LabVIEW.

Preparations of the ship: A number of modifications were made to prepare the model tanker for the measurement campaigns, like installation of beams for foundation of the turbine, installations and start-up of the diesel-electric plant, steering machinery, connection of shafts between propulsion motors and propeller shaft belt drives, installation of navigation lights and a GPS compass and mounting of an anemometer mast on the deck aft of the wheel house. Numerous sensors in the tanker were connected to the turbine's measurement system.

4.2 Development of prototype control and measurement system

A control system was developed for the prototype wind turbine on a National Instruments CompactRIO platform (crio). This section describes in some detail the functionality of the controls. The crio communicates with a laptop through an Ethernet cable. The laptop in the wheelhouse acts as the user interface wheelhouse (see Figure 7) and is also used to develop and download the programs to the crio's real time processor unit and FPGA (Field-Programmable Gate Array) respectively. The system is responsible for a number of tasks:

- Controlling the speed of the turbine in a control loop that runs at a rate of 100 Hz. The control loop measures the turbine speed, calculates the appropriate generator torque set point and outputs the generator current demand corresponding to that torque to the DC/DC converter.
- The other input signals to the system are read at a rate of 10 Hz.
- If data logging is activated, most signals in the system are saved to file. The sampling speed to file is 10 Hz.
- Communicating with the user interface and displaying values on the different instruments and graphs on the control panel.
- The wind turbine is manoeuvred from the laptop. By pushbuttons on the control panel, for example the tower could be raised and lowered, the yaw angle of the turbine can be controlled, the mechanical brake can be disengaged and the starter motor can be operated.
- Reading the wind speed and direction from the sonic anemometer.
- Reading the values from the GPS compass.

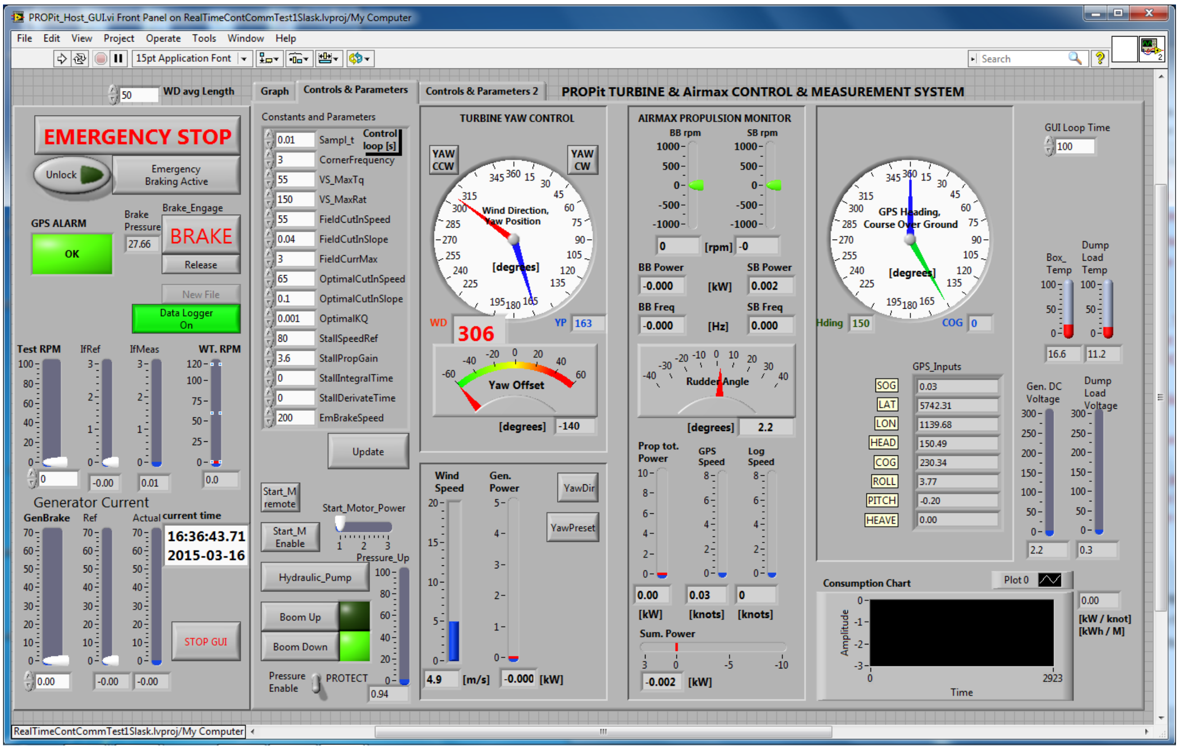


Figure 7 User interface on the laptop

The turbine speed controller uses two different control strategies. At low turbine speeds, which correlate to low wind speeds, the torque set point is calculated as the measured turbine speed in square times a constant. If the constant is well adjusted, the turbine speed will follow the wind speed and the turbine will operate at optimal tip speed ratio. This turbine is stall controlled, so when the turbine speed reaches the stall speed set point, a PI controller is engaged that limits the maximum allowable turbine speed. If the wind speed increases, it results in a steeper angle of the apparent wind on the air foil. Turbulence is increased and the turbine shaft power is limited.

4.3 Measurement campaigns

Sea measurement campaigns have been performed in the waters around the Öckerö island in the archipelago west of Gothenburg, in the period from December 2014 to March 2015. In relatively stable weather conditions fifteen measurement time frames were recorded. During each time frame the ship was kept at constant propeller shaft speed, and the helmsman tried to maintain a constant angle to the relative wind direction. During each time frame the Airmax has been operated with the

- wind turbine parked
- wind turbine active and no yaw offset
- wind turbine active and a yaw offset that orients the thrust force direction closer to the forward direction

The campaigns have been documented in detail, both in terms of general conditions and of measurement data. As a sample illustration, the map in Figure 7 shows some test runs. Start (green arrow) and stop (red arrow) defines one measurement run.

The measurement set up, in short, consists of:

- Apparent wind speed
- Apparent wind direction
- Ship speed over ground (SOG)
- Ship course over ground (COG)
- Ship heading
- Motor power
- Wind turbine power

Figure 8 Half wind port

4.4 Measurement results

In summary, the conducted sea measurement campaigns have provided significant observations, based on which patterns were identified and analyzed. Conditions such as waves, water current and wind are assumed to be “constant” within each test run, but due to differences in such conditions there is not enough certainty to compare results between different test runs. This is also the reason why no aggregate statistics have been built from all the campaigns.

From the fifteen measurement campaigns a number of observations and patterns have been identified, which are commented below. For the comparison of energy efficiency in the different operating situations “Net energy consumption” for ship propulsion is used, expressed as kWh/M and calculated as:

$$Net\ Energy\ Consumption = \frac{Motor\ power - Wind\ turbine\ power}{Ship\ speed\ over\ ground}$$

The following comments summarize the observations:

1) Operating the wind turbine has lowered the net energy consumption in all apparent wind directions tested, which are 45 degrees or more from straight head wind.
2) The direction of the thrust force can be controlled using a yaw offset, to contribute to the boat speed ahead.
3) It seems like there is a "sailing effect" in half wind and upwind conditions, meaning that the oncoming wind is being deflected aft, thus creating a reaction force forward on the boat. However, there are inconsistencies in this observation. This phenomenon has not been observed in all equivalent situations. When present, this phenomenon contributes to boat speed ahead, but the high yaw offset required means that electrical power production is sacrificed.
4) In apparent wind directions up to around 90 degrees from either side, it has been most efficient to use zero yaw offset in terms of net energy consumption. Maximizing the electrical energy output was more beneficial than controlling the thrust force and sailing effect.
5) In wind directions 100-120 degrees it has proven beneficial to apply a yaw offset of around 15-30 degrees. Then both the electrical power production and the controlled thrust force give good contributions and the net energy consumption becomes low.

Typical savings in net energy consumption were:

- 10% in apparent wind directions around 25 degrees
- 50% in apparent wind directions around 45 degrees port or starboard
- 65-80% in apparent wind directions around 80 -120 degrees port or starboard

4.5 Validation of simulation model

A turbine performance simulation model to estimate the net yield over a distribution of operating conditions has been developed. This is further described in chapter 5. In order to validate the simulation model, the simulation results have been compared to the actual measurements from the prototype tests on Stena Airmax.

Resemblance between simulated and measured power is high, although the power is slightly overestimated at low wind speeds. Uncertainty about the turbine characteristics, performance and control is a plausible explanation to the different power at low wind speeds. The resemblance in power is consistent with change of yaw angles up to 45 degrees. The graph in Figure 8 is an example of how the model validation is illustrated.

For the thrust there is a spread between the results of the simulation and the measurements. The measurements performed are few in number and under varying conditions. The ship has rather large inertia and may be accelerating or decelerating for a large portion of each time series collected.

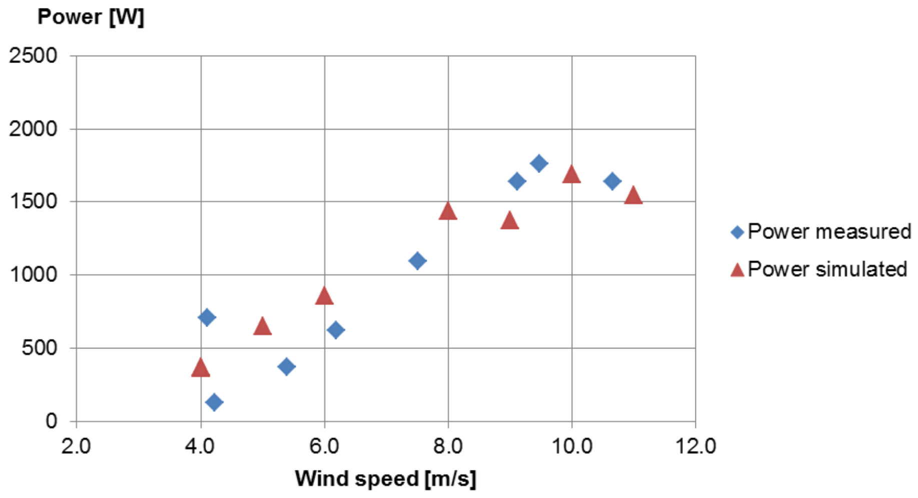


Figure 9 Measured and simulated power for yaw offsets 30 ± 5 degrees

The sea-current conditions are not known. These sources of error make it difficult to calculate the thrust force in a satisfactory manner. From the observed correlation it is fair to conclude that the simulation tool calculates the thrust correctly in principle. Measurement data is insufficient to clearly state the correctness of the magnitude of the thrust calculated or how it depends on the yaw offset.

5 Potential fuel savings

The ultimate objective of developing the technology is to achieve fuel savings, which in value exceed the cost of capital and operations to the extent that acceptable return on investment is attained. Making a generic investment case analysis involves a large number of variables and could from a market perspective be of slightly less interest as it would still be applicable to only the applied definitions and conditions. Instead the project has limited the simulations to well defined operational cases, which in themselves may have limited value for the overall understanding, but provide valuable indicators for the economic potential of the technology.

5.1 Specific wind conditions for North Atlantic crossings

In order to execute accurate simulations of the wind turbine performance, one has to examine and understand the prevailing wind conditions. Based on the wind distribution as actually measured onboard Wallenius ships for a number of routes in the North Atlantic and elsewhere, the wind distribution relative to the ship could be projected as in Figure 10. Any ship heading will provide the same relative wind direction distribution. In this instance, 270 degrees has been selected as the ship's heading. With an average wind speed at 9.8 m/s and the assumed ship speed at 13.6 knots there will be headwind (270 ± 45 degrees) 61 % of the time.

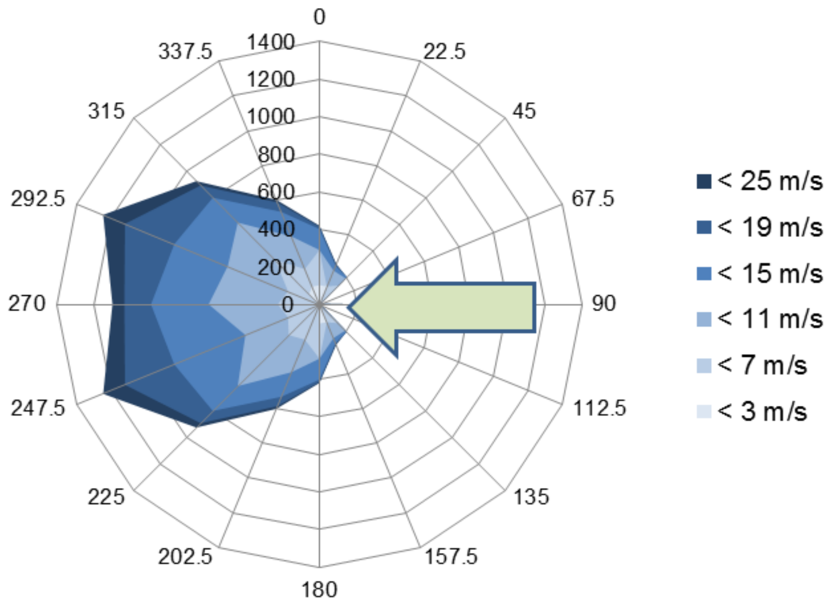


Figure 10 Wind rose for wind distribution (hrs/yr) relative to ship (arrow)

5.2 Modelling Atlantic crossings and results

The wind turbine performance has been simulated with the new simulation tool, the accuracy of which in turn has been validated by comparison with the sampled measurement data from the prototype sea measurement campaigns. Furthermore, the same pre-defined set of ship and turbine parameters were used as in phase one of the research project.

In a base case, the tool was used to estimate the produced energy and corresponding fuel savings for a Panamax tanker, equipped with two one megawatt wind turbines. For the ship which was assumed to trade in the North Atlantic the average annual fuel savings were calculated. At sea (assumed to be 80 % of the time) the saving was estimated to be 10 % or 1 100 m^3 annually. Under the assumption that the turbines could also be operated part of the time in port, the total annual saving was calculated to increase to 11 % or 1 200 m^3.

Furthermore a model has been created of how low- and high pressure areas might propagate over the north Atlantic sea. Depending on route planning, the ship might go straight through the centres of low and high pressures or take a slightly longer route to attain more favourable wind conditions for additional savings, see Figure 11.

Figure 11 High and low pressure weather systems

Based on this model, different wind rose distributions are obtained and corresponding fuel savings calculated. In a hypothetical but realistic example, route planning with respect to high and low pressure weather systems has demonstrated large potential to increase fuel savings, effectively due to the higher wind speeds. Taking a conservative approach based on the calculations performed, the average increase in fuel savings by route planning is 55 %.

Consequently, the base case expanded with some port operation and route optimization, the total annual fuel saving could be calculated to be 16 % or 1 800 m^3. With a heavy fuel oil (HFO) price of 354 USD/mt the annual fuel savings correspond to USD 590 000, for the calculated case.

It is notable that for a tanker operating at this given ship speed, the annual contribution from the forward thrust of the turbine is slightly negative, which then by far is compensated by the generated electrical power. Therefore, the actual dollar savings in an authentic business case must also be based on a fair estimation of how the electricity could be made beneficial to the ship's operation and at which efficiency rates.

6 Pre-study for demonstration project

6.1 Demonstration project design

Following extensive prototype trials and turbine performance analysis in this current project, the next development phase is a large scale demonstration project, for which a preliminary pre-study has been made. The proposed project design includes three phases:

- Turbine design and construction
- Onshore turbine operation
- Ship installation and real sea operations

The demonstration project should be formed as the platform for market introduction of the technology. Since it is a novel application of proven technology, the functionality must be convincingly demonstrated to shipowners and other prospective stakeholders, including safe and reliable operation and proven emergency procedures. The turbine control system must operate in an automated mode, be capable of being integrated with the ship's route optimization system and adapt the turbine to changing wind conditions in order to maximize fuel savings. In summary, the project should be the link between innovation and commercialization.

The project objective should be to "design, verify and test a large scale wind turbine on a ship in transit". The following milestestones are identified for the project:

- Design a customized wind turbine for a specific ship
- Order a new, tailor built or procure and modify a used wind turbine
- Establish supplier relations and a preliminary supply chain
- Installation, test and analysis/validation of results including fuel savings in real conditions
- Develop operating procedures and train crew for operation and maintenance
- Establish collaboration with partners for further development
- Collect feedback from all personnel concerned, for potential improvements

The project duration is planned for 16-18 months as indicated in Figure 10.

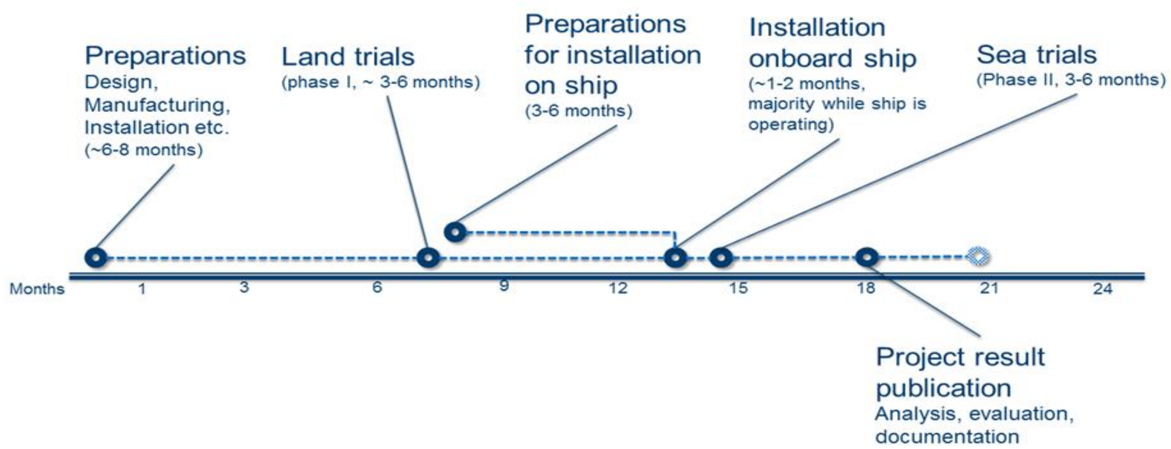


Figure 12 Demonstration project schedule

For the sea operations in the demonstration project, a suitable ship should be sought after and assessed against the following criteria:

- Long-distance shipping routes, or operating in areas with suitable wind conditions
- Low operating transit speed, preferably not higher than 14 knots
- Tanker or bulk ships with open deck space

Table 3 shows a preliminary budget estimate.

Table 3 Preliminary demonstration project budget

	MSEK
Design	1-2
Manufacturing	5-8
Installation and testing	1-2
Sea trials	1-2
TOTAL	**8-14**

6.2 Technical pre-feasibility study

Considering the fact that three bladed turbines are usually more stable and less prone to vibrations, than two bladed turbines, the demonstration project turbine should be three bladed.

A used turbine, acquired for a demonstration project, would need to undergo some modifications in order to cope with the different operating conditions in a ship application. The extent of such modifications has not been examined in this project but would need to be analysed in conjunction with an acquisition and as an early phase of a feasibility study. Notably, the tower will likely need to be replaced.

An evaluation has been conducted to state possible consequences for all major turbine components and estimated costs for possible adjustments of these. Most components will need modification, at least to some extent, to cope with the tilting of the turbine. The evaluation points to components with liquid containers like for instance lubrication oil and suggests that the main and yaw bearings, machine bed, gearbox and tower may need most attention in this aspect. Also, the ambition should be to find a direct drive turbine, since this means fewer components in the tower top.

Three possible solutions for the folding (tilting) mechanism have been investigated. The hydraulic solution as used in the current prototype, with modifications for a scaled version, has been set as reference in the comparison. More analysis than could be contained in this pre-study must be made by technical experts, covering areas like naval architecture, wind turbine design and manufacturing and hydraulic systems. The tilting is generally deemed to be feasible and as such comparable to for instance deck mounted cranes.

When connecting a wind turbine to a ship's electrical grid it must be equipped with full power conversion, such that the turbine operation does not compromise the stability of the ship's grid.

In the wind turbine design, (at least) the following aspects must be considered:

- Operation at large yaw angle offset
- Evaluation of consequences of wave motions on yaw system

- Conceptual drive train layout (see above)
- Offshore environment, water and salinity
- Ship motions causing accelerations and loads

6.3 Procurement of wind turbine

As mentioned, two options for turbine procurement were investigated, the first being the acquisition of a (probably) European, used turbine and the second to design and order a new built turbine from a low cost country supplier, likely in China.

Most of the used turbines on the European market are at least 15 years old and mainly located in Denmark, Germany and Holland. The price span is between kSEK 200-500 for the equipment only. For used turbines, some cost drivers for the necessary modifications were identified. In addition, the buyer must cover expenses for dismantling and transport. All turbines available on the used market today are three-bladed.

To order a new built turbine, specifications from this pre-study and from the prior project phase will serve as basis for tender documents.

6.4 Safety and risk assessment

The installation of wind turbine/s/ on merchant ships has been the object for further risk assessment through a structured method called SWIFT (**S**tructured**W**hat**IFT**echnique, ISO 31010) in a workshop conducted by Lloyd's Register. No show stoppers were revealed for the required approvals but a number of checkpoints were identified and added to the previous project report.

In the first phase, twenty-nine potential risks were identified, out of which five were selected for a deeper analysis in this workshop:

- The turbine cannot be folded
- The turbine becomes loose when folded
- The foundation fails
- The turbine cannot return to the position ready for stowing
- The cables are not properly installed on the ship

The workshop result was recorded in a systematic schedule, with "What if?" (risk), consequences, safeguards and recommendations, details which are not reiterated here. For each hazard the applicable regulation and requirements for fulfilment were identified. In general, the design concept was deemed acceptable from Class point of view and final approval would be based on an assessment of how the respective requirements are fulfilled and that the safety and environmental aspects of the systems can be demonstrated. The final approval would be subject to Flag Administration's eventual acceptance and/or comments.

7 Conclusions and Recommendations

The project was designed to both examine and validate prior research results in addition to making a survey of attitudes and opinions towards a novel technology for use in the marine environment. Conclusions could be drawn regarding fuel savings, modelling of turbine efficiency and how different stakeholder groups perceive the technology. A preliminary pre-study with a gap analysis for a demonstration project has been completed.

A simulation tool for modelling wind turbine performance under different operating conditions has been developed. A wind turbine prototype with a diameter of around six metres has been upgraded with new sensors and a control software system for more dynamic wind adaptation. Mounted on Stena's model tanker [Stena Airmax, scale 1:12] it has thus been used to sample measurement data under different wind conditions. By means of comparing the simulation tool output with the real measurement data, it has to a large degree been possible to validate the simulation tool. This is valuable as it allows further detailed analysis of different operating set-ups with varying ship and turbine data under varying conditions.

A turbine control system has been developed with which turbine modelling has been performed. The results show that active and dynamic turbine control can enhance performance by up to thirty percent in relation to prior calculations, which in itself is new in comparison with earlier research.

Considerable fuel savings have been estimated under given and realistic assumptions. The results are essentially in conformance with earlier reports, but can now be considered being of higher accuracy. For a Panamax tanker equipped with two one megawatt wind turbines and with a set of given conditions, annual fuel savings in the range of 16 percent have been estimated. Given an HFO price of USD 354/mt this means that the savings potential could be up to USD 590 000 per year on the given route. Certainly, there are high variations for seasons and routes and the research also points to opportunities for technology optimization, before going into commercialization.

To be proven successful, the technology must be adopted by the crew and other stakeholders. In general, attitudes and opinions about the proposed innovation are positive, with some concerns about training and work environment issues. The probability of gaining positive green goodwill was suggested by some interviewees while all expressed the need to be convinced about the financial benefits. Efforts should be made to demonstrate the results from real measurements with regards to actual fuel savings.

The demonstration project pre-study suggests the project objective to be to "design, verify and test a large scale wind turbine on a ship in transit". The project is designed for 16-18 months, to include three phases, turbine design and construction, onshore turbine operation and ship installation and real sea operations. For the latter, a suitable ship should be contracted, meeting criteria like long-distance shipping routes and/or operating in areas with suitable wind conditions, low operating transit speed and tanker or bulk ship with open deck space. The pre-study shows that turbine tilting is feasible, but that some critical components will need modification for this purpose. Two options for procurement were analysed, the acquisition of a used turbine and the ordering of a purpose built, tailor designed turbine, probably from China. From the risk assessment it was concluded that there are no show stoppers, but that final approval from Flag Administration will be required.

The project recommendation is to carry out a large scale demonstration project as a next step towards commercialization. This would include the remaining technical analysis identified in the pre-study, the completion of the risk assessment and technology verification.

A detailed engineering and feasibility study related to the selected ship must precede the actual construction and/or modification works. It is also strongly recommended to undertake extensive onshore testing of the wind turbine, with regard to operations under different wind conditions and yaw offsets, control system verification and the functionality of emergency procedures.

Ship based operations should be meticulously planned in order to exclude the risk for any whatsoever disturbance to the ordinary ship operations. The wind turbine performance should be carefully monitored and measured. As these will be undertaken on a ship in commercial operation, operating procedures and training must be part of the project plan.

From both the on- and offshore operations learnings should be documented with respect to how the working environment is affected and how the attitudes of different stakeholder groups may vary with the level of knowledge, experience and involvement with the project. With this as basis, a comparative update of the results from this current project should be made and evaluated.

Figures

Tables

References

This report is based on research in three work packages, with one or more sub reports for each, providing internal and external references. These are listed as references, per work package, with the respective authors.

Ref	*Author/s/*	*Reference document*	*Pages*
Work package #1 Wind turbine technology for ship application			
1	Mats Goldberg, Scandinavian Wind	SWE-0104-A Design principles for blades for wind turbines on ships	52
2	Mats Goldberg, Scandinavian Wind	SWE-0112-A Controller strategies for wind turbines on ships	17
3	Aleksander Stotsky, Chalmers University of Technology	Non-linear speed and yaw control for wind turbine powered vessels	24
4	Mats Goldberg, Scandinavian Wind	SWE-0117-A Two or three blades for Wind Turbines on Ships	5
5	Mats Goldberg, Scandinavian Wind	SWE-0118-A Comparison of Vortex, Vidyn and Cosine Law Methods for Calculation of Power and Thrust at Large Yaw Offsets	12
6	Christian Haag, Scandinavian Wind	SWE-0136-A Measurement results and impact of using wind turbine on a ship	55
7	Mats Goldberg, Scandinavian Wind	SWE-0140-B Calculations of fuel savings on arbitrary route on the North Atlantic using onboard wind speed measurements	4
8	Mats Goldberg, Scandinavian Wind	SWE-0138-C Calculations of savings using wind power on ships cruising the north Atlantic sea and other routes	29
9	Hamidreza Abedi, Chalmers University of Technology	Power and thrust calculations for varying yaw angle offset	1
Work package #2 Acceptance and attitudes towards wind powered ships			
10	Joakim Dahlman, Chalmers University of Technology	Acceptance and attitudes towards wind powered ships	20
Work package #3 Pre-study for Demonstration project			
11	Mats Goldberg, Scandinavian Wind	SWE-0127-A Wind Power on Ship - Wind Turbine for Pilot Project	17
12	Yu Huo, Lloyd’s Register	HAZID workshop report, Wind turbine installation on ship, phase II	5
13	Yu Huo, Lloyd’s Register	HAZID worksheet, phase II	5
14	Triinu Helena Laks, PROPit AB	Development and Demonstration of New Technology for the use of Wind Turbines on Ships	31